FORECASTING 24-HOUR VORTICITY CHANGE AT THE 500-mb LEVEL

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Lieutenant Commander, United States Navy

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IN
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ABSTRACT

Fjortoft's graphical method of prognosis of the 500-mb surface assumed relative vorticity change as being due to advection only. This study considers the total 24-hour relative vorticity change as consisting of two components, that due to 100% advection and that due to non-advective changes. Objective methods are developed for the prognosis of the latter. These changes are then added to the advective changes to give the total 24-hour relative vorticity change from which the 24-hour height change can be recovered.

The 500-mb velocity field is subjectively categorized into five types. For each type the non-advective relative vorticity change is correlated with a parameter determined from the spreading of the contours. Results for the five categories, when applied to data for the months of February and March 1957, are as follows:

Case	Velocity Field	Correlation Coefficient
I	Marked Cyclonic Curvature	0.60
II	Moderate Cyclonic Curvature	0.71
III	Negligible Curvature	0.79
IV	Moderate Anticyclonic Curvature	0.56
V	Marked Anticyclonic Curvature	0.10

Quantitative objective forecast rules are developed from the regression lines relating the non-advective relative vorticity change and the parameters for each of the five cases.

Using the developed technique the results of five 24-hour 500-mb test forecasts for the United States are presented.

These tests show an improvement of four feet in forecast height value for the entire forecast area as compared to the Fjortoft method. However, in considering only those points at which the computation was made an average improvement of 34 feet is noted.

Finally the persistence of non-advective relative vorticity changes is considered for its value as a height-change forecast tool. The results of seven forecasts prepared using this assumption indicate an improvement of 32 feet over the Fjortoft method for the entire forecast area.

The writer wishes to express appreciation to Professor W. D. Duthie for guidance and assistance in the preparation of this paper.

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TABLE OF SYMBOLS AND ABBREVIATIONS

ζ	Vertical component of the relative vorticity.
f	Coriolis parameter.
t	Time.
$\vec{V}$	Horizontal vector velocity of the wind.
ω	Individual rate of change of pressure with respect to time.
R	Non-advective relative vorticity change.
g	Gravitational force.
d	Grid distance.
z	Contour height.
$\bar{z}$	Space-mean contour height.
$\vec{V}_g$	Horizontal vector velocity of the geostrophic wind.
$\bar{\vec{V}}_g$	Horizontal vector velocity of the space-mean geostrophic wind.
x_1	Case I divergence parameter.
x_2	Case II divergence parameter.
x_3	Case III divergence parameter.
x_4	Case IV divergence parameter.
x_5	Case V divergence parameter.

$$S(\phi) = \int_0^{\phi} \frac{\Omega^2 d^2 \sin\phi \cos\phi}{m^2 g} \, d\phi$$

Ω	Earth's rotational velocity.
m	Map scale constant.
ϕ	Latitude.

$$\vec{C}_g = \frac{g}{f} \vec{k} \times \vec{\nabla} S(\phi)$$

CHAPTER I

INTRODUCTION

Fjortoft [1] developed a graphical method of forecasting the 500-mb constant pressure surface by the following procedure: 1) determine the distribution of relative vorticity at the 500-mb level; 2) advect this vorticity with the mean 500-mb flow; 3) obtain the 24-hour vorticity change by subtraction of these two fields; 4) recover the 24-hour height-change field from the 24-hour vorticity-change field; and 5) arrive at the prognostic chart by adding the height-change field to the current 500-mb chart. The assumptions involved in this procedure include barotropy, the geostrophic approximation, the neglect of the change of coriolis parameter and map scale with change in latitude, and the conservation of the mean 500-mb flow during the forecast period.

Many less restrictive models have been developed. Fjortoft, in the paper cited above, compensated for the change of coriolis force and map scale with latitude by adding a field, which is a function of latitude only, to the relative vorticity field and advecting this quantity. In another paper, Fjortoft [2] has developed a baroclinic model that assumes a functional relationship in the wind profile. Hesse [3] has included baroclinity with vertical motion due to terrain. Without question these more sophisticated graphical techniques will prove superior to arbitrarily selected statistical parameters. However, for the meteoroligist in the field,

the time involved in the preparation of the routine forecast must be held within strict limits. It is felt that techniques more complicated than the simple Fjortoft method would not be within the capabilities of the average Naval Weather Station.

The Air Weather Service [4] has tested the simple Fjortoft method as a means of objectively forecasting the 500-mb contour field for a 24-hour period. In the test consisting of 541 samples the Fjortoft method gave an average absolute error of 208 feet in the forecast 500-mb height, whereas subjective techniques employed at the USAF Weather Central gave an average error of 207 feet. It was concluded that:

> objective use of the graphical method presented by R. Fjortoft produces 24-hour 500-mb prognostic charts of about the same quality as those produced by skilled forecasters in a weather central.

It was further concluded that the time required for the preparation of the complete forecast was within the capabilities of the average weather detachment.

Because of its assumptions of barotropy, the Fjortoft method is incapable of forecasting the changes in the intensities of circulation; hence it will not show the rapid and spectacular deepening of lows aloft, which are ascribed to the baroclinic state of the atmosphere. This paper is an attempt to develop statistical methods which will indicate the magnitude of baroclinic changes in the upper air and, together with the Fjortoft procedures, provide an improved

objective forecast routine for the meteorologist in the field.

CHAPTER II

THEORETICAL DEVELOPMENT

The vorticity equation is expressed in isobaric coordinates as follows:

$$\frac{d(\zeta+f)}{dt} = -(\zeta+f)\vec{\nabla}\cdot\vec{V} - \nabla\omega \times \frac{\partial V}{\partial p}\cdot\vec{k} \qquad (1)$$

where ζ is the vertical component of the relative vorticity, f is the coriolis parameter, $\vec{V}$ is the horizontal velocity, p is the pressure, and $\omega = \frac{dp}{dt}$. Vectors are indicated by overlining, and the vector operator $\vec{\nabla} = \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k}$ has its usual vector meaning. Expanding the left hand side of this equation,

$$\frac{d(\zeta+f)}{dt} = \frac{\partial(\zeta+f)}{\partial t} + \vec{V}\cdot\vec{\nabla}(\zeta+f)$$

$$= \frac{\partial\zeta}{\partial t} + \vec{V}\cdot\vec{\nabla}_H\zeta + \vec{V}\cdot\vec{\nabla}_H f + \omega\frac{\partial(\zeta+f)}{\partial p} \qquad (2)$$

and combining with the right hand side we have:

$$\frac{\partial\zeta}{\partial t} = -\vec{V}\cdot\vec{\nabla}_H\zeta - \vec{V}\cdot\vec{\nabla}_H f - \omega\frac{\partial(\zeta+f)}{\partial p} - (\zeta+f)\vec{\nabla}\cdot\vec{V} - \vec{\nabla}\omega \times \frac{\partial\vec{V}}{\partial p}\cdot\vec{k} \quad (3)$$

or the local rate of change of relative vorticity is equal to the sum of terms representing horizontal advection of relative vorticity, horizontal advection of the change of coriolis parameter with latitude, vertical advection of absolute vorticity, generation of absolute vorticity due to divergence in the velocity field, and generation of absolute vorticity by the "tilting" term. If we let the sum of these

last four terms be equal to R, this equation may be expressed as

$$\frac{\partial \zeta}{\partial t} = -\vec{V} \cdot \vec{\nabla}_H \zeta + R. \tag{4}$$

Fjortoft, in his simplest model, considered R negligible and forecast the local rate of change of relative vorticity by advecting the relative vorticity at the mean geostrophic wind velocity. If statistical methods were utilized to determine the quantity R and this value added to the advected field, the forecast would be improved.

The purpose then is to develop an objective prognostic routine consisting of the following steps: 1) determine the relative vorticity field; 2) advect this field with the mean geostrophic wind; 3) graphically calculate the change in relative vorticity due to advection; 4) add to this change field an empirically determined correction to compensate for the neglected terms in the vorticity equation; and 5) recover the height-change field and the contour field from the corrected vorticity-change field.

Well known methods [5] are available for graphically computing the field of relative vorticity. Making use of the geostrophic approximation, the relative vorticity can be expressed as

$$\zeta = \frac{g}{f} \nabla^2 z \tag{5}$$

where Z is the contour height and ∇^2 is the Laplacian

operator in the plane. Written in finite difference form

$$\zeta = \frac{g}{fd^2}\left[Z_1 + Z_2 + Z_3 + Z_4 - 4Z_0\right] \qquad (6)$$

we have a means for determining the field graphically, where the subscripts denote values of Z at the four sides and at the center of a square grid, and d is the grid distance. If the small variation of f with latitude is ignored, the relative vorticity at any point may be represented by

$$\zeta = \bar{Z} - Z \qquad (7)$$

where

$$\bar{Z} = \frac{1}{4}\left[Z_1 + Z_2 + Z_3 + Z_4\right]$$

is the space-mean contour height.

Now combining equations (4) and (7), and replacing $\vec{V}$ by the more conservative velocity field $\vec{\bar{V}}_g$, we have

$$\frac{\partial}{\partial t}(\bar{Z} - Z) = -\vec{\bar{V}}_g \cdot \nabla_H(\bar{Z} - Z) + R \qquad (8)$$

where $\vec{\bar{V}}_g$ is the geostrophic mean wind.

If the equation for relative vorticity (5) be differentiated with respect to time, we have

$$\frac{\partial \zeta}{\partial t} = \frac{g}{f}\nabla^2 \frac{\partial Z}{\partial t}. \qquad (9)$$

The solution to this partial differential equation offers the means of recovering the height-change field from the forecast vorticity-change field. Fjortoft [1] has developed a graphical solution to this equation by expanding in a con-

verging infinite series and then neglecting the smaller terms. If all but the first two terms are neglected, the height change is approximated by

$$\Delta z = -\nabla \zeta - 2\overline{\Delta \zeta} \tag{10}$$

where Δ denotes the 24-hour change and the bar denotes the space-averaged value of the quantity. For a less accurate approximation, all but the first term may be ignored giving

$$\Delta z = -\Delta \zeta \tag{11}$$

or the 24-hour height change is equal to the negative of the 24-hour vorticity change.

CHAPTER III

PROCEDURE

Used in this research was a series of 500-mb charts of the United States and the Pacific Ocean prepared by the staff analysts at the U. S. Naval Postgraduate School, Monterey, California, during the months of February and March 1957.

The field of 24-hour vorticity change due to advection was determined by the Fjortoft method. This field was then subtracted from the actual vorticity-change field as calculated from the next day's actual vorticity. This field, R in equation (8), was considered to be the vorticity change due to baroclinic influences in the atmosphere. The forecasting of this quantity will be considered in the next chapter.

In constructing vorticity charts by graphical means a grid distance of 6 degrees of latitude at 60 degrees North was considered to give best results. Isopleths of relative vorticity were advected at 100 percent of the space-mean 500-mb wind. Most authors [4, 6] suggest 80 percent as being best in order to compensate for the use of the 500-mb level as the level of non-divergence. However, as the objective of this paper is to forecast the effects of divergence on the vorticity field, 100 percent of the mean wind was used.

Some difficulty was encountered in the graphical techniques of adding and subtracting due to fields consisting of many small, closed centers. This difficulty was usually

overcome by drawing intermediate isopleths. However, on a few occasions the field was still not adequately determined; but it was evident that this occurred only when the vorticity change was small and due entirely to advection.

CHAPTER IV

FORECASTING VORTICITY CHANGES

As discussed in Chapter II, two of the sources of non-advective relative vorticity changes are divergence in the velocity field and vertical motions in the atmosphere. An attempt will be made to forecast these changes by purely statistical means.

Scherhag [7] states that where upper contours converge, an "entrance zone", pressure rises will occur due to transverse convergence, and where upper contours diverge, a "delta zone", pressure falls will occur due to transverse divergence. O'Connor [8] states that convergence and upper height rises are associated with low speed winds approaching straight or cyclonically curved strong contour gradients or with high speed winds approaching anticyclonically curved weak contour gradients, and that divergence and upper height falls are associated with high speed winds approaching cyclonically curved weak contour gradients. These two statements provide the parameters that will be correlated with non-advective vorticity changes in order to forecast the magnitude of the changes due to divergence in the velocity field.

O'Neill [9] conducted an investigation as to the validity of the above statements for forecasting height-change centers and concluded that, although qualitatively correct, the rules devised did not show sufficient correlation between observed and forecast height change to provide a quantitative fore-

cast. However, it is felt that even though no high correlation existed between total height-change and selected parameters, such a correlation may exist when non-advective vorticity change is the dependent variable.

An attempt was made to measure the radius of curvature as one of the parameters to be used. Because of difficulties in determining where to make the measurement this was abandoned in favor of using five subjective classifications: marked cyclonic curvature, moderate cyclonic curvature, negligible curvature or straight contours, moderate anticyclonic curvature, and marked anticyclonic curvature. These five cases will be examined in detail.

Case I - Marked cyclonic curvature. There were a total of 21 configurations that were considered to fall within this classification in the series of maps examined. All were associated with major troughs, one located over the west coast of the United States moving slowly eastward and the other over the Western Atlantic which moved off the chart.

The parameter used to measure the divergence of contours is defined as $x_1 = d_t - d_i$ where d_t is the distance in degrees latitude between 400 feet of contour at the trough line, and d_i is the distance between 400 feet of contour at the upstream inflection point of the same contours. The contours selected are those in the geometric center of the flow around the trough. Figure 1 shows the configurations involved and the method of measuring x_1.

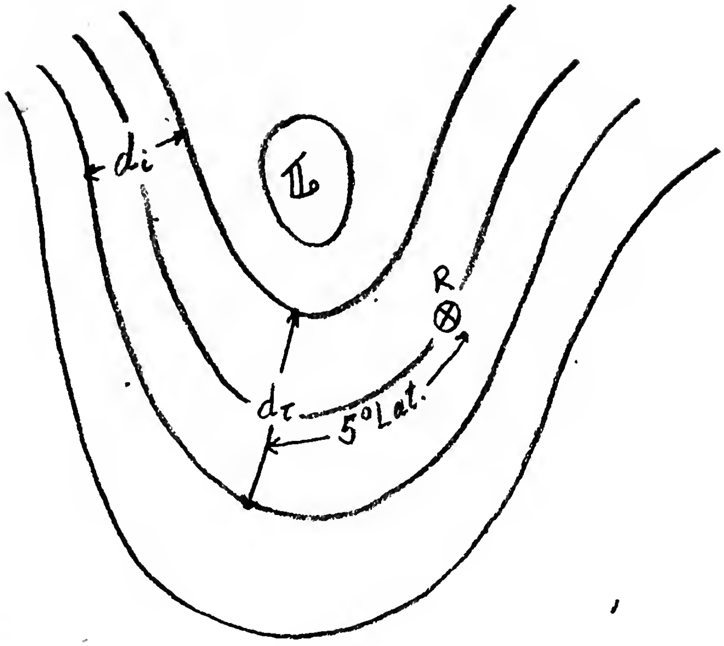

Figure 1

Contour Pattern for Case I and

Method of Measuring x_1

Multiple correlation techniques of R with two independent variables, magnitude of the vorticity change and location relative to the trough line of the vorticity-change center, were attempted, but no significant correlation was found to exist[1]. In 19 cases there were closed centers of non-advective vorticity change, the mean position of which was located approximately on the middle one of the three involved contours at a distance downstream from the trough line of five degrees of latitude. Therefore, this was taken as the position at which R was measured.

Figure 2 is the scatter diagram of the values obtained in the investigation of Case I examples with the regression line of R on x_1, $R = 116 + 46\ x_1$. The correlation coefficient between the two variables was calculated to be 0.60.

It is to be noted that there were only 4 cases in which the value of x_1 was negative, that is, the geostrophic wind at the trough was greater than at the inflection point. If the four cases were eliminated, the correlation coefficient would be improved.

<u>Case II - Moderate cyclonic curvature</u>. Fifteen examples were observed in this classification. These were areas of large longitudinal extent with generally smooth flow and little change in contour spacing.

[1]These techniques were applied in all cases with similar results.

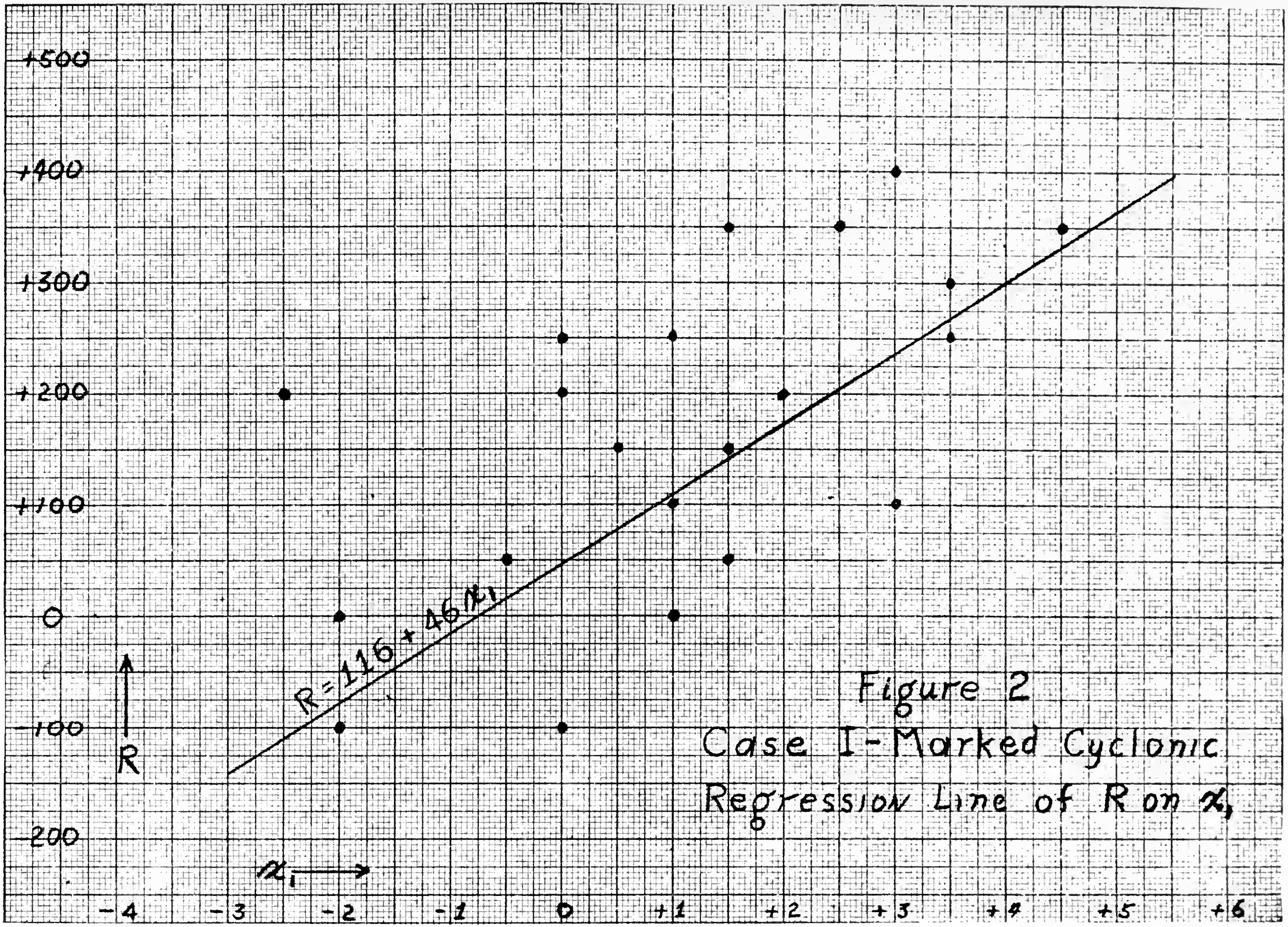

Figure 2
Case I - Marked Cyclonic
Regression Line of R on x_1

The values of the parameter selected for the measurement of divergence, x_2, were obtained as in Case I. There were only four closed centers of non-advective vorticity change associated with this configuration of contours, the mean position of which was different from that in Case I; however, in the interest of consistency, the same location for measureing R was used in both cyclonic cases.

Figure 3 is the scatter diagram for the 15 Case II examples. A regression line of R on x_2, $R = 24 + 78 x_2$, was obtained. These data gave a correlation coefficient of 0.71.

Case III - Negligible curvature. There were 18 examples observed under this classification. They were located in broad troughs or ridges and in areas of extensive zonal flow.

The value of the parameter x_3 is defined as $x_3 = d_2 - d_1$ where d_1 is the distance in degrees latitude between 400 feet of contour at the upstream end of the straight contours, and d_2 is the distance in degrees latitude between the same contours at the downstream end. The contours used were those in the center of the flow. The value of R was measured at the downstream end of the center contour. Figure 4 indicates the parameters used.

The scatter diagram, figure 5, gives the results of the Case III examples with the regression line of R on x_3, $R = 19 + 45 x_3$, with a correlation coefficient of 0.79.

Case IV - Moderate anticyclonic curvature. There were 15 examples in this category, located in areas of broad zonal flow. There was little change in contour spacing involved

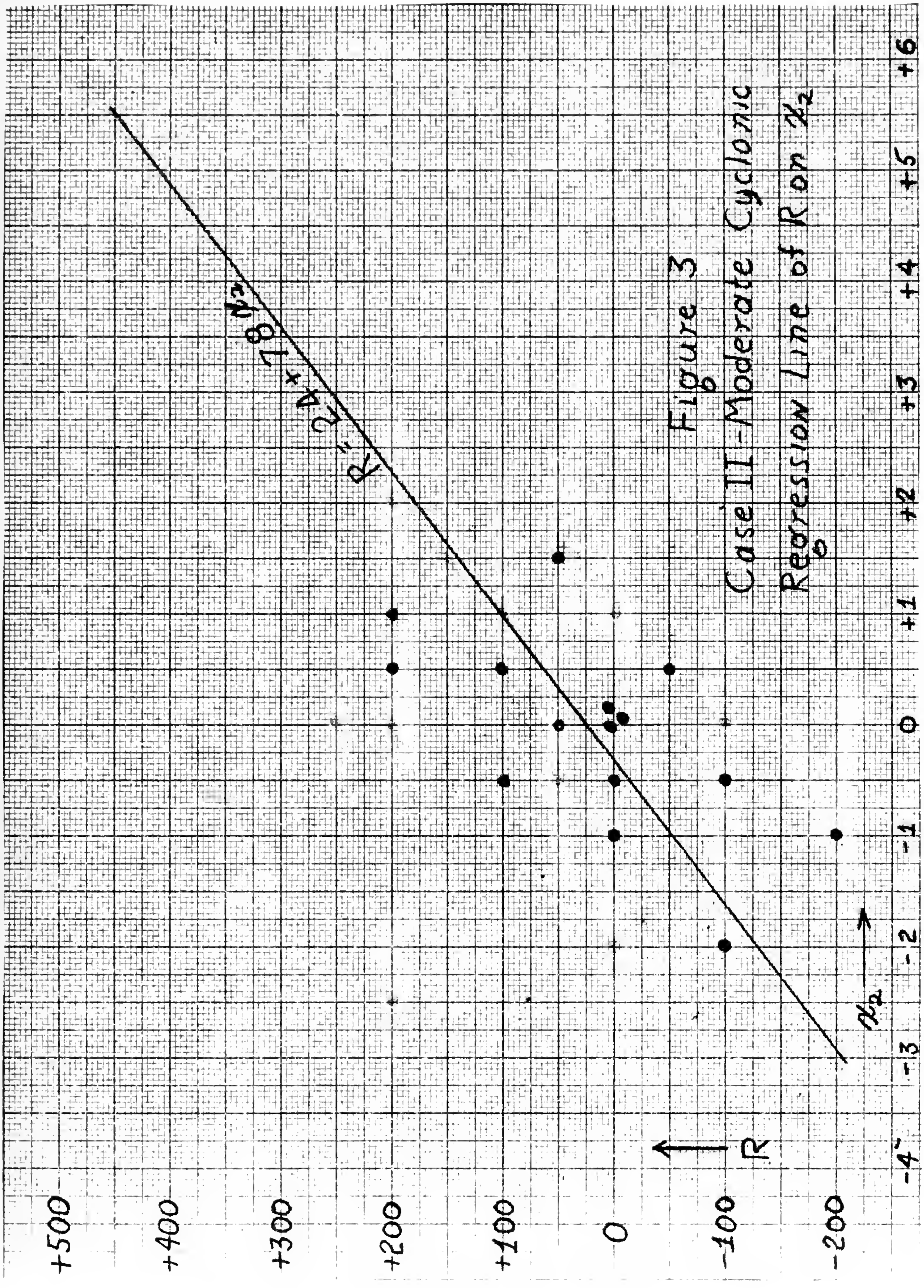

Figure 3
Case II - Moderate Cyclonic
Regression Line of R on x_2

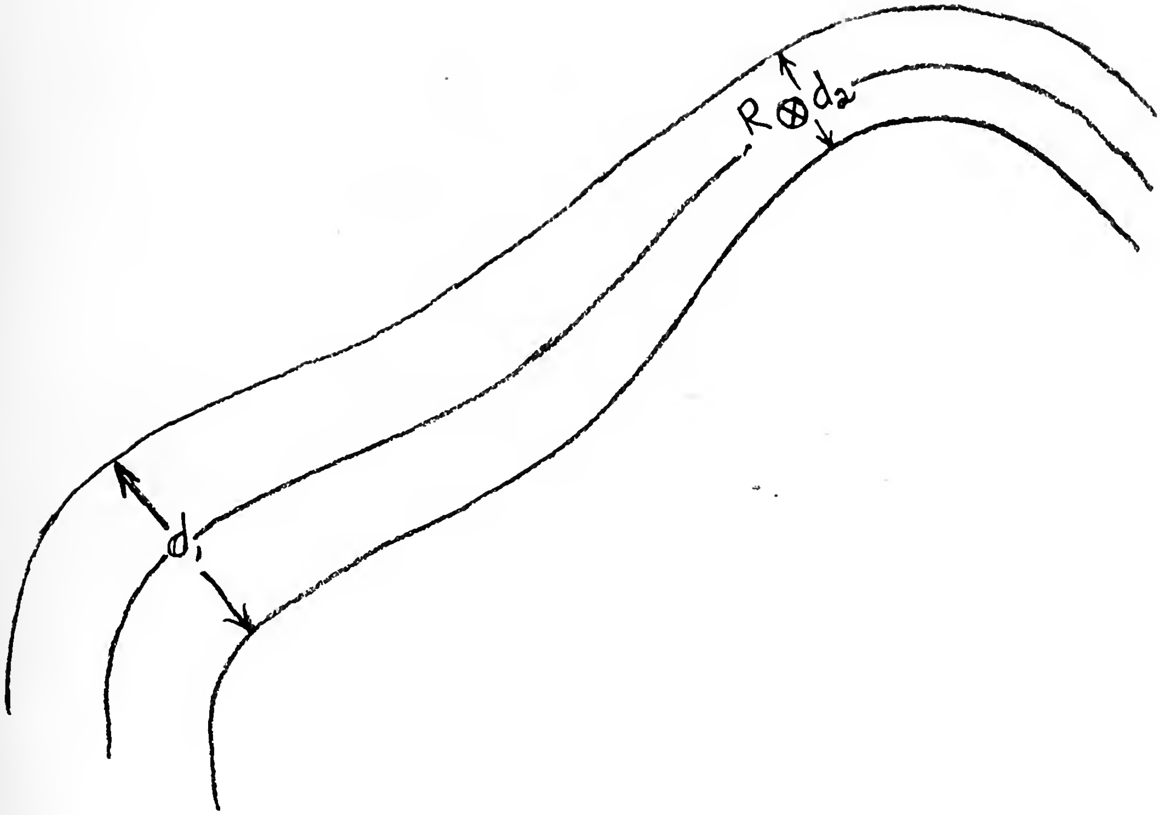

Figure 4

Contour Pattern for Case III and

Method of Measuring x_3

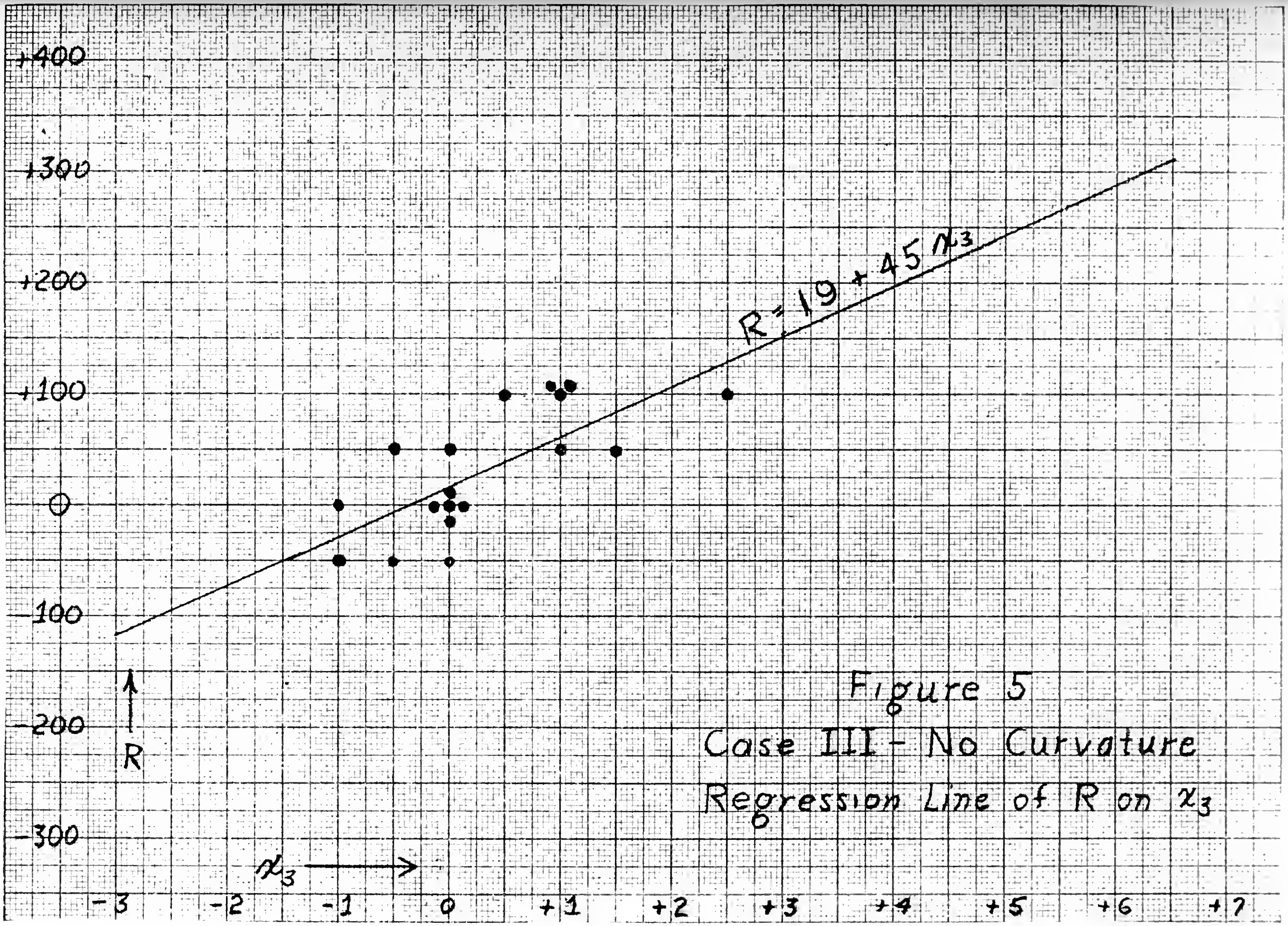

Figure 5

Case III - No Curvature

Regression Line of R on x_3

in these areas.

The value of the divergence parameter, x_4, is defined as $x_4 = d_r - d_1$, where d_r is the distance in degrees latitude between 400 feet of contour at the ridge line, and d_1 is the distance in degrees latitude between the same 400 feet of contour at the inflection point upstream. The value of R was taken five degrees of latitude downstream from the ridge line on the contour of least height value of the three used. Figure 6 indicates the method of measuring the parameters.

The scatter diagram, figure 7, indicates the results of the Case IV investigation with the regression line of R on x_4, $R = -40 + 53x_4$. A correlation coefficient of 0.56 was obtained.

<u>Case V - Marked anticyclonic curvature</u>. There were 24 configurations that were classified in this category, all directly upstream or downstream from the major troughs of Case I.

The value of the parameter x_5 was obtained in the same manner as x_4 in Case IV. There were 17 closed centers of non-advective vorticity change involved with a mean position 5 degrees of latitude downstream from the ridge line near the contour of least height value. R was measured at this point.

Figure 8 is the scatter diagram for Case V with the regression line of R on x_5, $R = -155 + 6x_5$. A correlation coefficient of 0.10 was obtained.

The results of the above part of the investigation are summarized in Table I.

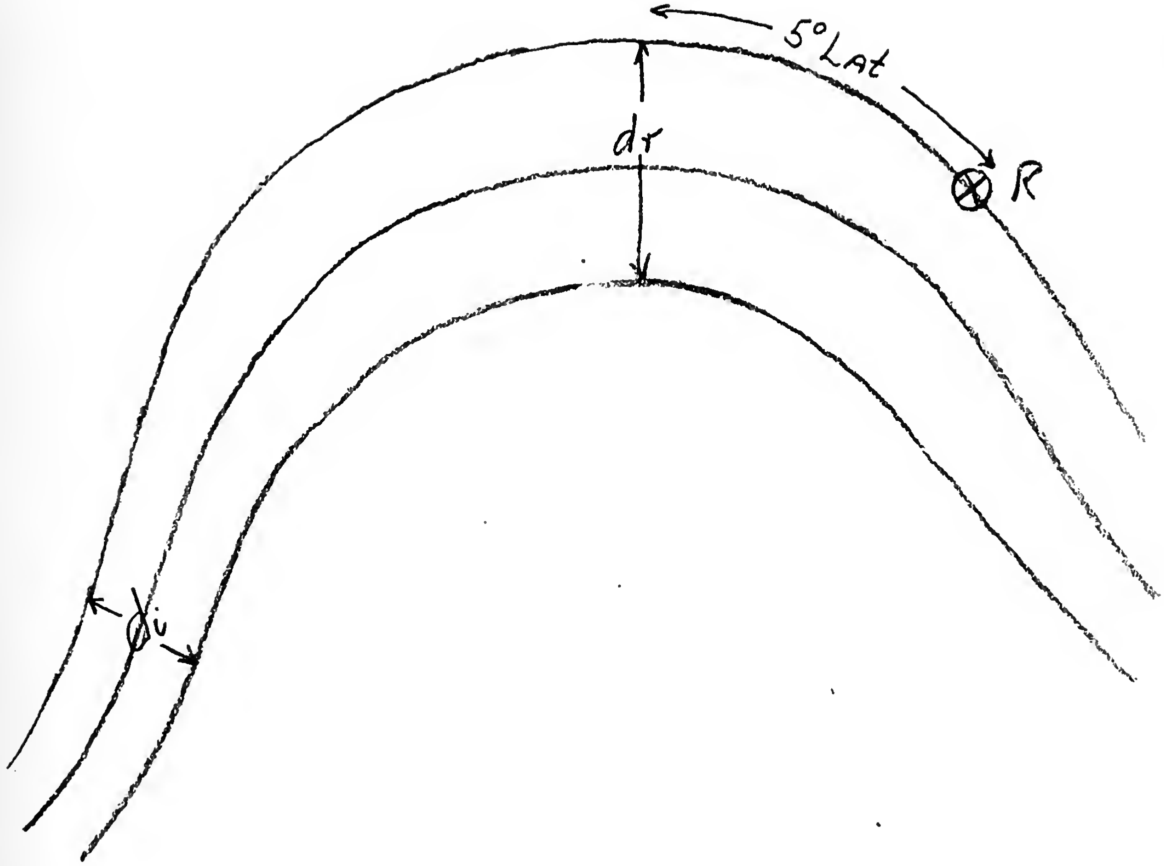

Figure 6

Contour Pattern for Case IV and

Method of Measuring x_4

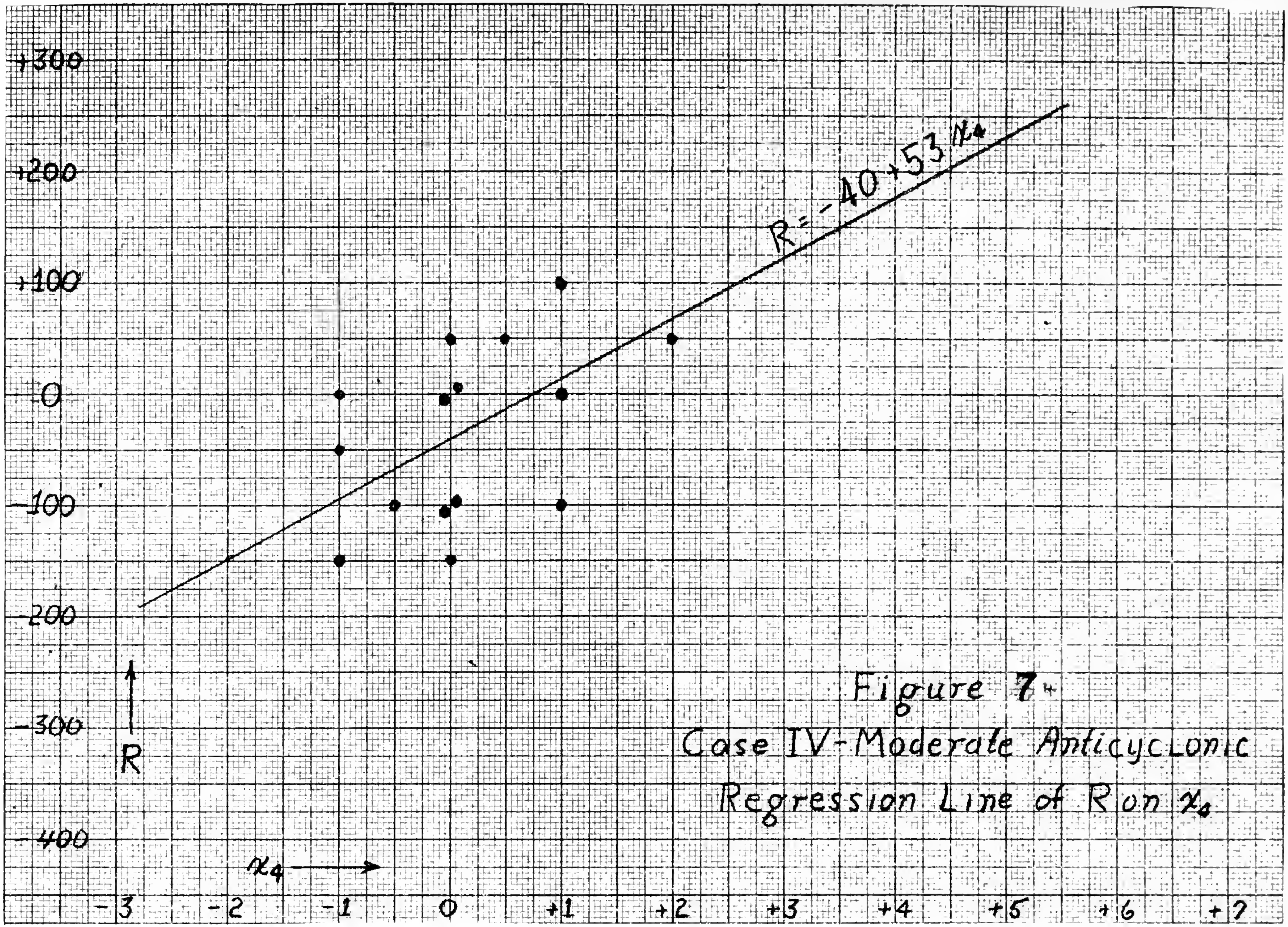

Figure 7.
Case IV - Moderate Anticyclonic
Regression Line of R on x_4

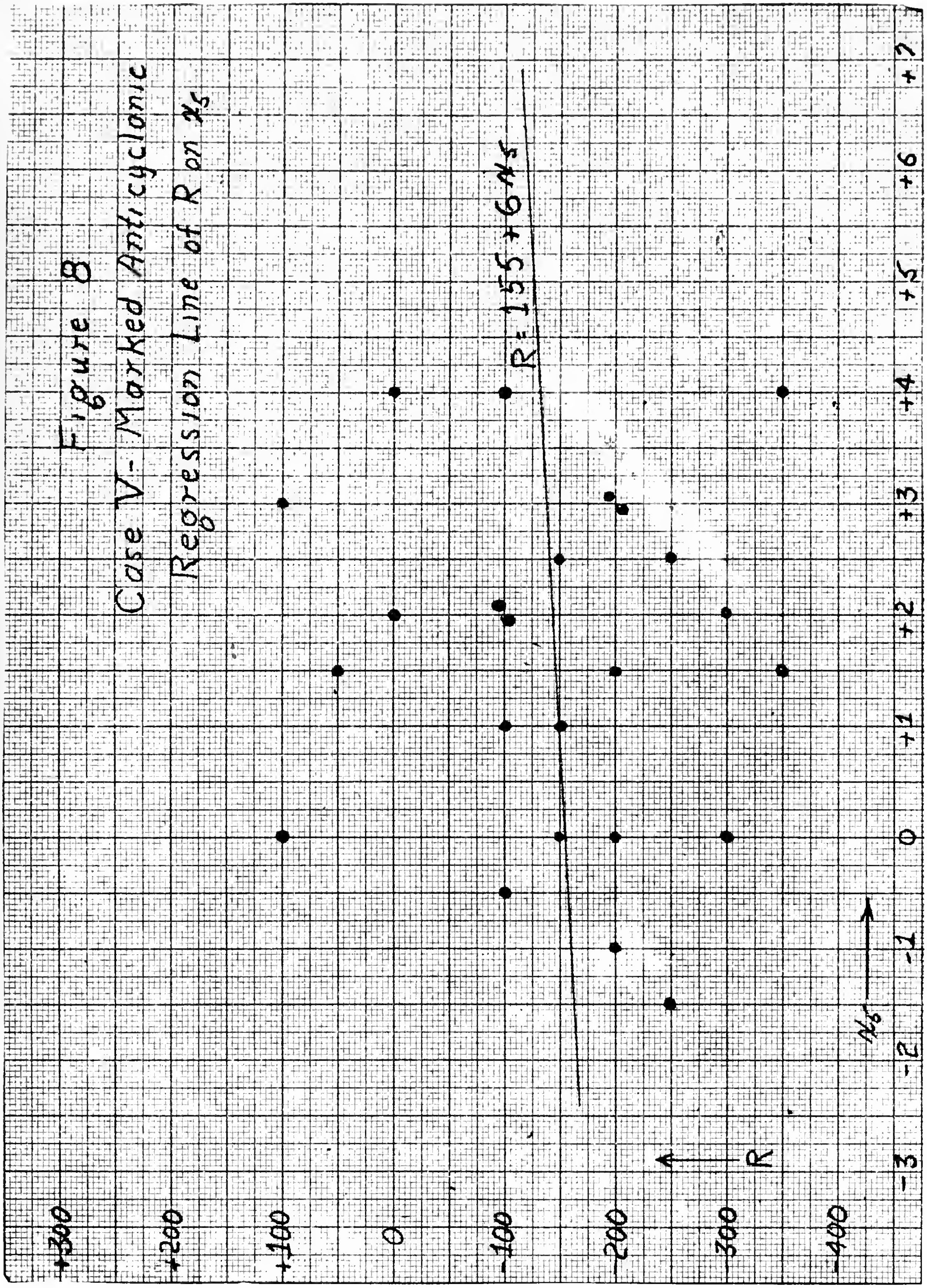
Figure 8
Case V - Marked Anticyclonic
Regression Line of R on x_s
R = 155 + 6 x_s
+300
+200
+100
0
-100
-200
-300
-400
R
-3
-2
-1
0
+1
+2
+3
+4
+5
+6
+7
x_s

Case I

Number of Examples	21
Parameter (°Lat.)	$X_1 = d_t - d_1$
Regression Line	$R = 116 + 46x_1$
Correlation Coefficient	.60
Mean value of R (feet)	165
Standard deviation of R (feet)	153

Case II

Number of Examples	15
Parameter (°Lat.)	$x_2 = d_t - d_1$
Regression Line	$R = 24 + 78x_2$
Correlation Coefficient	.71
Mean value of R (feet)	20
Standard deviation of R (feet)	95

Case III

Number of Examples	18
Parameter (°Lat.)	$x_3 = d_2 - d_1$
Regression Line	$R = 19 + 45x_3$
Correlation Coefficient	.79
Mean value of R (feet)	30
Standard deviation of R (feet)	50

Case IV

Number of Examples	15
Parameter (°Lat.)	$x_4 = d_r - d_1$
Regression Line	$R = -40 + 53x_4$
Correlation Coefficient	.56
Mean value of R (feet)	-30
Standard deviation of R (feet)	80

Case V

Number of Examples	24
Parameter (°Lat.)	$x_5 = d_r - d_1$
Regression Line	$R = -155 + 6x_5$
Correlation Coefficient	.10
Mean value of R (feet)	-150
Standard deviation of R (feet)	130

TABLE I

As indicated earlier, in addition to the divergence in the velocity field, there is another source of change in the local relative vorticity that would appear to lend itself to statistical methods: that due to vertical motions in the atmosphere. An attempt was made to derive a correction for the effects of vertical motions.

Case I samples were divided into two categories: Those in which the major trough was on the lee side of the continental divide and those in which the major trough was on the windward side. Lines of regression and correlation coefficients of R were computed for each of these two categories. There were no significant differences. However, the number in each case was very small. Results would be more conclusive if examples were taken of the two categories in Case III, the straight flow case, due to its higher correlation factor, but the series of maps used in the research was not adaptable to such analysis. Time considerations prohibited further testing.

Conclusions. The correlation coefficients in Cases I, II, and III are significant at the 95% level. It would be indicated that in the regions of cyclonically curved or straight contours a corrective field can be added to the advected field of relative vorticity that will improve the forecast for a 24-hour period. The correlation coefficient in Case IV is significant at the 90% level, and in Case V there was no statistical significance. In the cases of anticyclonically curved contours, the radius of curvature of the

contour appears to be much more critical, but with moderate curvature a correction can be applied that will improve the forecast. With marked curvature a parameter that more accurately determines the deviation from the gradient wind will have to be used.

It should be noted that the local rate of change of relative vorticity in the absence of marked curvature of contours is due primarily to advection. Table I shows the small values of the means and standard deviations of non-advective changes in these cases.

CHAPTER V

INDEPENDENT TEST RESULTS

The 500-mb prognostic techniques developed in Chapter IV were tested with a series of five independent forecasts prepared during the month of April 1957.

The 24-hour relative vorticity change due to advection was determined by the Fjortoft method using 100% of the mean 500-mb wind as the advective field. The 24-hour relative vorticity change due to other sources was prepared by plotting the values of R determined from the regression formulas, and then subjectively drawing the R field over the entire map. The sum of these two fields was considered the total 24-hour relative vorticity-change field, from which, the 24-hour height-change field was recovered by the application of equation (10).

The prognostic charts prepared were verified on the basis of forecast and observed 24-hour height changes. Thirty-six grid points on each map, for a total of 180 cases, were used in this phase. As a basis of comparison of the value of the method of prognosis, forecasts were also prepared by the unmodified Fjortoft method.

The root-mean-square errors for the two methods showed no significant difference when all the 180 points were considered, being 146 feet for the Fjortoft method and 142 feet for the other. However, if only those points were considered for which a value of R had been actually calculated, a significant improvement was made. There were a total of 37 such

points for the five maps. The root-mean-square error in forecast height-change for these points was 135 feet as compared to an error of 169 feet for the forecast prepared by the unmodified Fjortoft method.

Conclusions. The results of the test forecasts indicate that the objective prognosis of the 500-mb constant pressure chart cannot be accomplished by the methods developed herein for the following reasons: 1) subjectivity enters into the classification of the contour pattern; 2) the rules are applicable at only a few points; 3) it is impossible to draw an extended area chart of the values of R given the values at only these few points; and 4) the method fails in areas of marked anticyclonic flow. However, for limited application, it is believed that the values determined from the configuration of the contour field can be subjectively employed to improve the Fjortoft prognostic chart.

CHAPTER VI

FURTHER STUDIES

A further study was conducted in order to attempt to discover continuously variable parameters for forecasting the non-advective relative vorticity change. Used in this phase of the research was a series of maps for November 1955.

There was no indication of any continuity in the paths of the centers of values of R. Hence extrapolation was of no prognostic value.

A measure of the baroclinity of the atmosphere is the number of intersections of isotherms and contours on a constant pressure surface. An attempt was made to use this principle for forecasting in two ways. First, the actual density of the solenoids was plotted against the values of R. This was done in several different ways, for example, by counting the number of intersections of isotherms and contours within a radius of three degrees of latitude of the point at which R was measured. Second, multiple correlation was attempted between the gradients of temperature and height value and R. Neither of these attempts met with success.

Persistence of the values of R was determined to be the most successful prognostic tool in the forecasting of R. That is to say, for forecasting the value of R at any point on the chart, best results were obtained by making the assumption that $\frac{\partial R}{\partial t} = 0$.

For the seven maps considered, using 100% of the mean flow for the advection of relative vorticity, the Fjortoft method gave a root-mean-square error of 211 feet in forecast height change as approximated by equation (11). Using persistence as the forecast of R this error was reduced to 179 feet.

As mentioned in Chapter I, Fjortoft [1] indicated a method of compensating for the change of coriolis force and map scale with latitude. In this improved model, equation (8) was replaced by

$$\frac{\partial}{\partial t}\left[\bar{z} - z + s(\varphi)\right] = -\left(\vec{\bar{V}}_g + \vec{C}_g\right) \cdot \vec{\nabla}\left[\bar{z} - z + s(\varphi)\right] + R$$

where

$$s(\varphi) = \int_0^{\varphi} \frac{\Omega^2 d^2 \sin\varphi \cos\varphi}{m^2 g} \, d\varphi$$

and Ω is the earth's rotational velocity, d is the grid distance, m is the map scale constant, φ is the latitude, g is gravity, and

$$\vec{C}_g = \frac{g}{f} \vec{k} \times \vec{\nabla} s(\varphi)$$

is a steady easterly wind. Also mentioned earlier was the evidence that 80% of the advective field gives better results.

The same forecasts were prepared using this more refined Fjortoft method and the recommended 80% wind. The root-mean-square error in forecast height change was 203 feet. Using persistence as the forecast for R, this was reduced to 177 feet.

It appeared that persistence of R relative to the contour field, rather than to the actual geographic position, might

give superior results, but evidence was inconclusive.

Conclusions. Any conclusions reached concerning the above results must be qualified ones because of the meagerness of the tests on which they are based. Although the improvement in root-mean-square error in the forecast height change is statistically significant, only one series of maps was studied. A different synoptic situation may conceivably produce entirely different results. Further testing will have to be conducted before objective application of the rules would be warranted.

The primary effort in this research was directed at developing forecast rules based on the configuration of the contour field. The methods developed failed in objective application for the reasons given in Chapter V. As a result of the further study, these objections have been overcome by assuming the persistency of R. Preliminary results indicate that this assumption is a valid one and can be objectively applied to prognosis of the 500-mb contours. Final conclusions can be reached only after further testing.

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